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Research on WEDM process optimization for PCD micro milling tool

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Abstract

An initial study on WEDM process optimization for PCD micro milling tool has been carried out. With a orthogonal design of roughing and finishing condition experiment of PCD, a largest difference of WEDM parameter is obtained to calculate the influence of those parameter on cutting speed for roughing operation and surface roughness Ra and metamorphic layer thickness for finishing operation. For roughing operation, peak current and voltage pulse width are the dominant WEDM parameters; while for finishing operation, Peak current, peak voltage are the largest influence of parameters on cutting speed. With WEDM optimized parameters, a quadrilateral PCD micro milling tool is fabricated with CTB002 PCD material. Tool edge radius is 6.7 μ m.

Keywords: WEDM; micro milling,;poly-crystalline diamond (PCD),;micro tool,;design of experiment (DOE)

1. Introduction

With the development of mechanical, electrical, medical, optical, and biochemical area, micro products and related components increase rapidly along with some applications in these area [1]. Micro machining processes are the very hot research area [2,3,4]. Micro milling is one of micro machining technology having the ability to machine various engineering materials with a relatively high material removal rate, and at same time allows for the complex three dimensional structures in the field of micro machining. One of the most important aspects for micro milling is micro milling tool. Micro milling tool generally is made of ultra hard material which includes tungsten carbide [5], poly-crystalline diamond (PCD) [6], natural diamond, PCBN and so on.

High stiff micro mills are required in order to prevent tool breakage and bending, which have a negative influence on the cutting process. Furthermore, hardness and abrasive resistance of traditional tool tungsten carbide materials is insufficient for micro machining. The tool shape easily deteriorates due to the rapid wear of the cutting edges, thus requiring the employment of other hard tool materials [7]. There are many excellent properties that poly-crystalline diamond possesses, such as very high hardness, good abrasive resistance, small friction coefficient and high binder phase strength of polycrystalline structure. Compared with cemented carbide, poly-crystalline diamond is more suitable to produce sharp and durable micro tool. However, because of its high hardness and wear resistance, PCD micro milling tool is very difficult to shape tool edges.

Precision grinding and non-traditional machining processes including electrical discharge machining (EDM)[9], wire cut EDM[5,10], laser machining and focused ion beam sputtering process (FIB)[8], are often used as manufacturing processes of micro milling tools. Compared with grinding, cutting force is very slight in the EDM process, which does not cause the workpiece deformation. Compared with grinding and FIB, EDM processing efficiency is higher, thereby greatly reducing manufacturing cost.

Metal cobalt in poly-crystalline diamond is used as

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a binder, which results in conductivity of PCD. However, conductivity of PCD is poor than most metal. The unreasonable EDM electrical parameters can easily lead to the poor PCD surface quality and the low machining efficiency. To optimize the electrical parameters, including voltage pulse width, peak voltage, peak current and pulse interval, WEDM experiment of PCD composite film is carried out. And surface roughness Ra and the cutting speed of PCD are measured to obtain the optimal WEDM process. With the optimal WEDM process, a PCD micro milling tool is manufactured.

2. Experimental set-up and procedure

2.1. Workpiece material and equipment

The experimental material is PCD composite film (CTB002/CTB010/CTH025) made by Element Six. Diamond particle size of PCD composite film (CTB002/CTB010/CHT025) is respectively 2μm, 10μm and 25μm. The mechanical properties are listed in Table 1.

Table 1. Mechanical properties of poly-crystalline diamond

Parameter	CTB002	CTB010	CTH025
Density [g/cm3]	3.85	3.85	3.86
Grain Size[μm]	2	10	25
Young's Modulus[GPa]	900	900	925
Poisson's Ratio	0.086	0.086	0.086
Thermal conductivity[W/(m*K)]	560	560	560
Compressive Strength[GPa]	7.55	7.60	7.61
Transverse Rupture Strength[GPa]	1.04	0.96	0.92
Fracture Toughness [MPa·m1/2]	6.55	7.31	8.61
Knoop Hardness[GPa]	50	50	50

The WEDM experiment is carried on QWD-760 wire EDM machine manufactured by VOLLMER (Fig.1). Zinc - copper wire of 0.2mm diameter is used as the electrode wire of the WEDM experiment. The machine tool has a horizontal wire feed direction and an automatic measuring and erosion in one set up operation. A water-based dielectric fluid will be used for improving surface roughness of the machined part by taking away erosion material.

Fig1. QWD-760 wire erosion machine

2.2. Experimental procedure

In order to optimize the WEDM process for PCD micro tool manufacturing, the critical machining requirements must be identified. The optimization of WEDM process includes productivity during roughing operation and quality during finishing operation. In the both operations, the electrical parameters including voltage pulse width, peak voltage, peak current and pulse interval, are both changed to identify the influence on surface quality and machining rate of PCD.

Because of the large number of the electrical parameters that should be considered for roughing and finishing operation, a design of experiment (DOE) that is carried out, statistically evaluate the parameters in different levels to identify the dominant WEDM parameters that most effect roughing productivity and finishing quality. For roughing operation and finishing operation, the electrical parameters and corresponding levels are listed in Table 2 and Table 3, respectively. All other EMD condition requirements will be constant. To accurately measure cutting time, the cutting length of PCD is 3mm, as showed in Fig. 2.

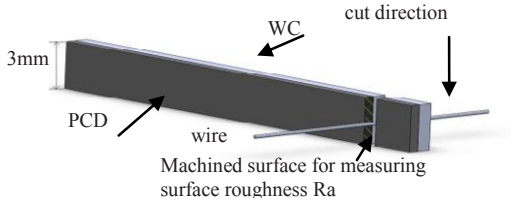

Fig2. PCD experimental cutting mode

Table 2. L16 roughing condition experimental array

Test #	Peak voltage [V]	Peak current[A]	Pulse width [μs]	Pulse interval [μs]
1	140	20	4	110
2	140	24	6	140
3	140	28	8	170
4	140	32	10	200
5	160	20	6	170
6	160	24	4	200
7	160	28	10	110
8	160	32	8	140
9	180	20	8	200
10	180	24	10	170
11	180	28	4	140
12	180	32	6	110
13	200	20	10	140
14	200	24	8	110
15	200	28	6	200
16	200	32	4	170

Table 3. L16 finishing condition experimental array

Test #	Peak voltage [V]	Peak current [A]	Pulse width [μs]	Pulse interval [μs]
1	120	3	2	20
2	120	5	3	30
3	120	7	4	40
4	120	9	5	50
5	140	3	3	40
6	140	5	2	50
7	140	7	5	20
8	140	9	4	30
9	160	3	5	50
10	160	5	4	40
11	160	7	2	30
12	160	9	3	20
13	180	3	5	30
14	180	5	4	20
15	180	7	3	50
16	180	9	2	40

In the WEDM process for PCD micro tool manufacturing, there are roughing operation and finishing operation. For roughing operation, the cutting speed of PCD will be observed in three times per PCD grade in order to use mean values for analysis. For finishing operation, PCD Surface roughness Ra is measured by Mahr Perthometer M1. Three measurements on different areas were conducted for machined surface, and an average value of the surface roughness Ra was used for evaluating the machined surface quality. With Leica DVM5000 microscope, three dimensional structure of the PCD surface is reconstructed to generate the mosaic images.

By comparison of the variation of cutting speed and surface roughness (Ra), the optimal electrical parameters will be obtained, which correspond to maximum cutting speed for roughing operation and minimum surface roughness (Ra) for finishing operation.

3. Results and analysis

3.1 Roughing condition experiment

Roughing condition experiment is conducted on all three grades of PCD composite material. According to the DOE of roughing operation, 16 experiments are conducted on each PCD grade. Each experimental set of 16 is repeated three times per PCD grade in order to use mean cutting speed values for analysis. Kjm is the arithmetic average of cutting speed value of the mth level of the jth parameter that will be obtained to influence of WEDM parameters on cutting speed.

Fig. 3-6 show the cutting speed of PCD as functions of WEDM parameters, which will be intuitively drawn the influence of those parameters on the cutting speed. In the study, cutting speed tend to be faster with the increasing of Peak voltage, Peak current and Voltage pulse width. However, cutting speed tend to obtain a peak with the increasing of pulse interval. There are two causes for this result. One is that erosion materials are not immediately removed from gap when pulse interval is short, and anther is that the number of discharge in unit time is fewer when pulse interval is long.

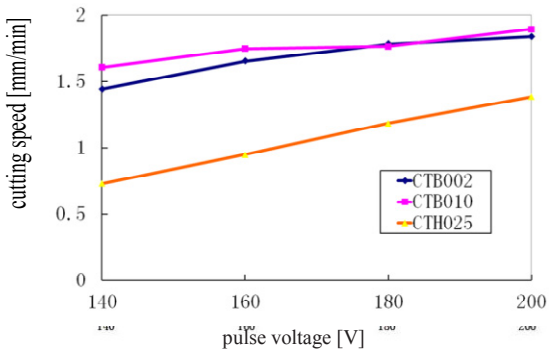

Fig. 3 Effect of pulse voltage on cutting speed

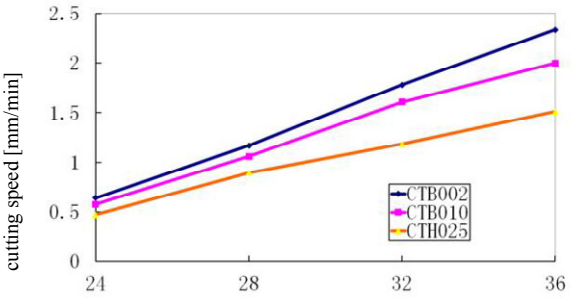

Fig. 4 Effect of pulse current on cutting speed

Fig.3-6 also shows the influence of diamond grain size on the cutting speed. Cutting speed tend to be slower with the increasing of diamond grain size. The cutting speed for CTH025 PCD is significantly slower than CTB002 and CTB010 PCD. Therefore, CTB002 and CTB010 PCD are used to carry on finishing condition experiment.

After extracting the optimal parameter level for each PCD grade from Fig. 3-6, the specific optimized parameter values can be obtained in Table 4.

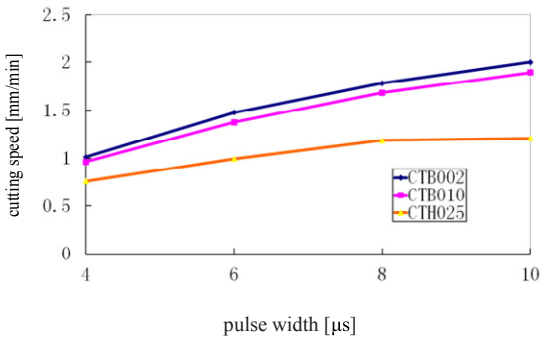

Fig. 5 Effect of pulse width on cutting speed

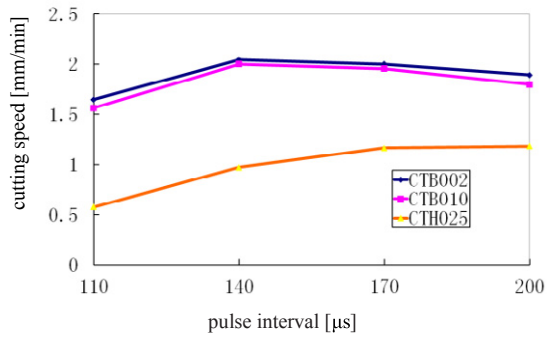

Fig. 6 Effect of pulse interval on cutting speed

Table 4. The specific optimized parameter values for roughing operation

	Peak voltage[V]	Peak current[A]	Voltage pulse width[μs]	Pulse interval [μs]
CTB002	200	36	10	130
CTB010	200	36	10	130
CTH025	200	36	10	150

The influence of WEDM parameter on the cutting speed of PCD grade is found by the largest difference of WEDM parameters. To calculate a largest difference, simple calculations are conducted using Eqs.1, where Kjm is the arithmetic average of cutting speed value of the mth level of the jth parameter.

Rj = max (Kj1, Kj2, Kj3,…, Kjm)-min(Kj1, Kj2, Kj3,…, Kjm) (1)

By observing the largest difference of each WEDM parameter on the cutting speed of PCD as shown in Table 5, it is determined which parameter has the large influence on the cutting speed of PCD. For CTB002 and CTB010, the peak current and voltage pulse width have the largest effect on cutting speed of PCD. However, for CTH025, the largest influence of parameters on cutting speed is peak current, peak voltage and pulse interval.

Table 5. Influence of WEDM parameter on the cutting speed of PCD

	Peak voltage[V]	Peak current[A]	Voltage pulse width[μs]	Pulse interval [μs]
CTB002	0.3967	1.6971	0.9888	0.3941
CTB010	0.2876	1.4231	0.9321	0.4348
CTH025	0.6559	1.0402	0.4486	0.6054

3.2 Finishing condition experiment

For finishing condition experiment, 16 experiments are only conducted on CTB002 and CTB010 PCD. Firstly, roughing operations of PCD are conducted with a special WEDM parameters (Peak voltage 180V, Peak current28A, Voltage pulse width 6μs, Pulse interval 150μs). With L16 finishing condition experimental array as shown in Table 3, finishing condition experiment will be conducted on the machined surface.

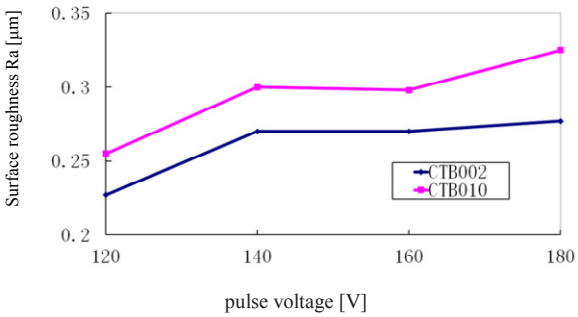

Fig. 7 Effect of pulse voltage on Ra

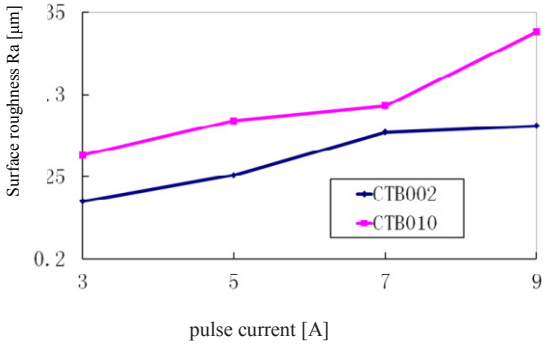

Fig. 8 Effect of pulse current on Ra

Fig. 7-10 show the surface roughness Ra of machined PCD surface as functions of WEDM parameters, which will be intuitively obtained the effect of those parameters on surface roughness Ra. In the study, surface roughness tends to be larger with the increasing of Peak voltage and Peak current. Fig.8-11 also show the influence of diamond grain size for each PCD grade on surface

roughness Ra, which is that surface roughness tends to be larger with the increasing of diamond grain size.

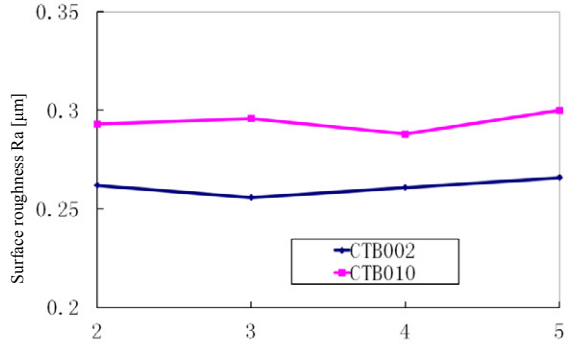

Fig. 9 Effect of pulse width on Ra

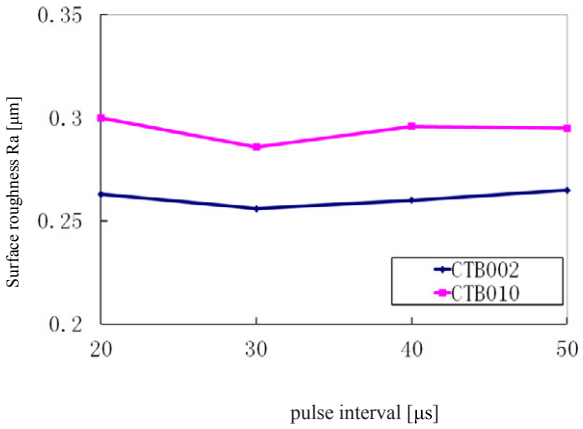

Fig. 10 Effect of pulse interval on Ra

After extracting the optimal parameter level for each PCD grade from Fig. 8-10, the specific optimized parameter values can be obtained in Table 6.

The influence of WEDM parameter on surface roughness of PCD grade is found by the largest difference of WEDM parameters. To get a largest difference, simple calculations are conducted using Eqs. 1, where K_{jm} is the arithmetic average of the surface roughness of the mth level of the jth parameter .

Table 6. The specific optimized parameter values for finishing operation

	Peak voltage[V]	Peak current [A]	Voltage pulse width[μs]	Pulse interval [μs]
CTB002	120	3	3	30
CTB010	120	3	4	30

By observing the largest difference of each WEDM parameter on surface roughness of PCD as shown in Table 7, it is determined which parameter has the large influence on surface roughness of PCD. For CTB002 and CTB010, the Peak voltage and Peak current width have the largest effect on cutting speed of PCD.

Table 7. Influence of WEDM parameter on the surface roughness of PCD

	Peak voltage[V]	Peak current[A]	Voltage pulse width[μs]	Pulse interval [μs]
CTB002	0.05	0.046	0.01	0.009
CTB010	0.07	0.075	0.012	0.014

4. Manufacture

Fig. 11 shows a typical PCD tool fabrication process. In cutting and edging of tool fabrication process, the roughing and finishing operation of WEDM will be conducted to get the utmost accuracy and best surface quality, which can prevent abnormal tool wear and poor machined surface quality during the micro milling process. In order to verify the performance of the WEDM optimized parameters, a quadrilateral PCD micro milling tool is fabricated with CTB002 PCD material (Fig. 12). Besides, three-dimensional structure of PCD micro milling tool is reconstructed with application of LEICA DVM5000 microscope (Fig. 13), and tool edge radius is 6.7μm.

a. cutting b. welding c. edging

Fig. 11 Typical PCD tool fabrication process

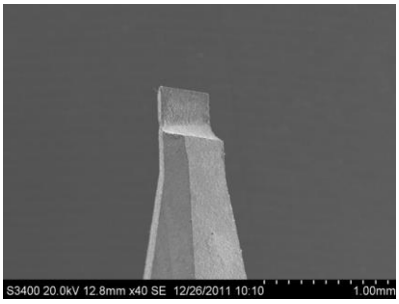

Fig. 12 A quadrilateral PCD micro milling tool

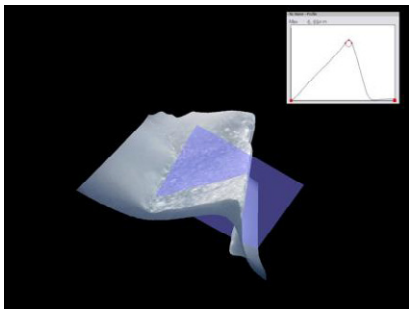

Fig.13 Tool edge radius 3D-reconstruction(6.7 μ m)

5. Conclusion

An initial study on WEDM process optimization for PCD micro milling tool has been carried out. With a orthogonal design of roughing and finishing condition experiment, a largest difference of WEDM parameter is obtained to calculate the influence of those parameters on cutting speed for roughing operation and surface roughness Ra for finishing operation.

It is found that peak current and voltage pulse width are the dominant WEDM parameters for roughing operation; while for finishing operation, the largest influence of parameters on cutting speed is peak current, peak voltage. The roughing and finishing optimal parameter values are extracted.

With WEDM optimized parameters, a quadrilateral PCD micro milling tool is fabricated with CTB002 PCD material. And tool edge radius is 6.7 μm.

Acknowledgements

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